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Astroparticle Physics – 2016/17

Werkcollege 9 – 10.11.2016

Problem 33 Cherenkov detector

In an air shower experiment the secondary particles at ground level can be detected with Cherenkov detectors (see also Problem 11). At the Pierre Auger Observatory, the particle detectors are filled with water (refractive index $n = 1.33$).

a) Knowing that particles move at the speed $v = \beta c$ through the medium, show that the angle Θ between the particle trajectory and the radiation direction of the Cherenkov radiation is given by

$$\cos\Theta = \frac{1}{\beta n}.$$

b) Calculate Θ for relativistic particles.

c) Calculate the minimum energy of protons, muons, and electrons to radiate Cherenkov radiation (Cherenkov threshold) in a generic medium with refractive index n.

d) Considering the wavelength range between 400 and 600 nm, the amount of photons emitted through Cherenkov radiation per unit of length is equal to

$$\frac{dN}{dx} = 380\ Z^2\ \sin^2\Theta \text{ photons cm}^{-1},$$

where Z is the atomic charge of the particle. Compute the number of photons emitted through Cherenkov emission by a relativistic muon (i.e. $\beta = 1$), traveling the distance of 1 cm in water. Compare the result to the amount of photons emitted by the same muon traveling the same distance in a plastic scintillator detector.

Hint: Consider ionization energy losses only and the muon being at the minimum of ionization accordingly to the Bethe-Bloch formula. Consider for the plastic scintillator $\rho_{scint} = 0.8$ g cm^{-3} and a light-yield $LY = 10^4$ photons MeV^{-1}. The light-yield is defined as the amount of photons emitted by a scintillator material per amount of energy released inside it.

Problem 34 Fluorescence light

Electrons (and positrons) in air showers excite the nitrogen molecules in the atmosphere to emit fluorescence light. The light is mainly emitted in the wavelength interval from 300 to 400 nm. The maximum of the emission is at 337 nm. Each electron (or positron) stimulates the emission of about 4 photons per meter of its trajectory.

Calculate the energy radiated in fluorescence light at the shower maximum for an air shower induced by a primary proton with an energy of 10^{20} eV (see also Problem 31).

Hint: Use the number of electrons at shower maximum according to a Heitler model. Assume the electrons propagate for one radiation length X_0 and $\rho_{air} = 1.23$ g l^{-1}. To calculate the energy of the photons, use the maximum emission only, i.e. the 337 nm line.

Which fraction of the primary energy is radiated as fluorescence light?

Problem 35 Fluorescence detector

With imaging fluorescence telescopes the amount of fluorescence light in air showers can be measured as a function of the depth in the atmosphere. The total amount of light collected is proportional to the shower energy.

Use a Heitler model and derive the relation (1), which describes the number of photons per square meter registered in a detector at distance r.

Using the number of electrons at shower maximum the number of photons registered per square meter in a detector at a distance r to the maximum of a shower with energy E_0 can be estimated as

$$\nu_\gamma = \frac{N_e X_0 N_\gamma}{4\pi r^2} \approx 790 \, \frac{\gamma}{\text{m}^2} \, A^{-0.046} \left(\frac{E_0}{\text{EeV}}\right)^{1.046} \frac{1}{(r/10 \text{ km})^2}, \tag{1}$$

where $N_\gamma \approx 4$ γ/m is the fluorescence light yield of electrons in air and $X_0 = 36.66$ g cm^{-2} the radiation length. Absorption and scattering in the atmosphere are neglected in this simple estimate, thus, the equation gives an upper limit for the registered photons.

Estimate the number of fluorescence photons measured in a telescope with a collecting area of 12 m^2 at a distance of 20 km to the shower maximum for a shower induced by a proton with an energy of 10^{20} eV.

The solutions will be discussed during the werkcollege on 10.11.2016 in HG02.702.
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Lecture web site: http://particle.astro.ru.nl/goto.html?astropart1617